

VOLCANIC-ASSOCIATED MASSIVE SULFIDE DEPOSITS (MODELS 24a-b, 28a; Singer, 1986a,b; Cox, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Volcanic-associated massive sulfide (VMS) deposits range from lens shaped to sheet-like bodies of sulfide-mineral-rich rock spatially associated with volcanic rocks ranging in composition from basalt to rhyolite (fig. 1). VMS deposits can be divided into three general categories. Cyprus-type deposits (Model 24a; Singer, 1986a) tend to be small, medium-grade deposits rich in copper and zinc. They are generally lens or mound shaped accumulations of massive pyrite developed in ophiolite-related, extrusive basalt sequences. They are typically underlain by copper-rich "stringer-zones" composed of anastomosing quartz-sulfide mineral veins in extensively chloritized basalt. Kuroko deposits (Model 28a; Singer, 1986b) are typically developed in intermediate to felsic volcanic rock and are generally interpreted to have formed in extensional environments associated with arc volcanism. They are commonly high grade and can be very large. Relative to Cyprus-type deposits, they generally have much higher contents of zinc, lead, silver, and antimony, which reflects the composition of their felsic volcanic host rocks. They also have mound-like morphology and the abundance of coarse clastic sulfide minerals within many of these deposits attests to a moderately high energy, seafloor depositional setting. Kuroko-type deposits also tend to be underlain by copper-rich stringer zones and commonly have well developed geochemical zonation with progressive zinc, lead, and silver enrichment both vertically and laterally away from vent centers. Besshi-type deposits (Model 24b; Cox, 1986) are present in mixed volcanic-sedimentary environments. Deposits of this type are commonly hosted by turbidites that have been intruded by basaltic sills. These deposits are typically copper-rich and contain small abundances of lead and other lithophile elements. In contrast to other volcanic-hosted deposits, many Besshi-type deposits form thin, laterally extensive sheets of pyrrhotite- and (or) pyrite-rich massive sulfide rock; however, the characteristics of Besshi-type deposits vary considerably. Slack (1993) presents an expanded definition of Besshi-type deposits that includes deposits such as those in the Ducktown, Tenn., district and the large Windy Craggy deposit in British Columbia.

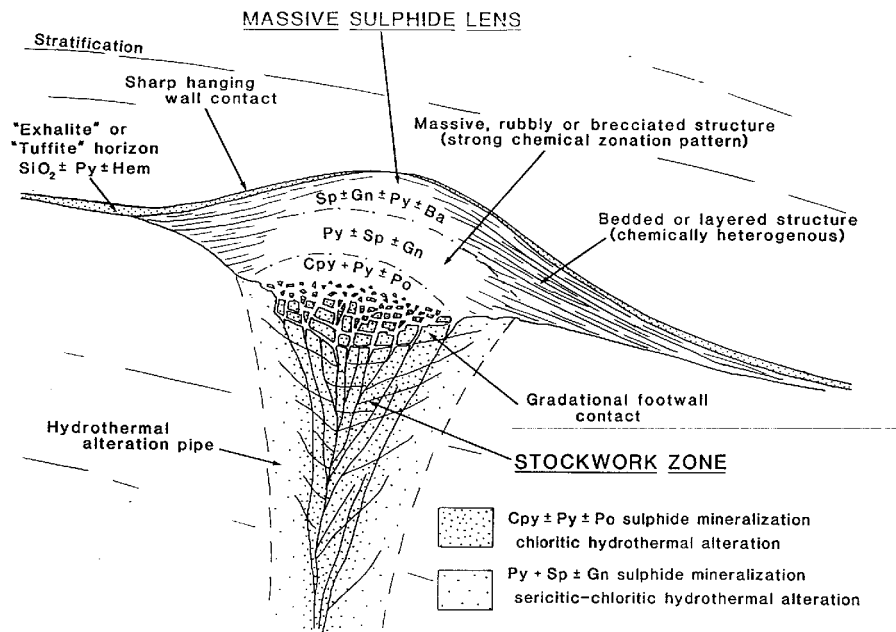


Figure 1. Essential characteristics of an idealized volcanogenic massive sulfide deposit (modified from Lydon, 1984). Mineral abbreviations as follows: Sp, sphalerite; Gn, galena; Py, pyrite; Ba, barite; Cpy, chalcopyrite; Po, pyrrhotite; and Hem, hematite.

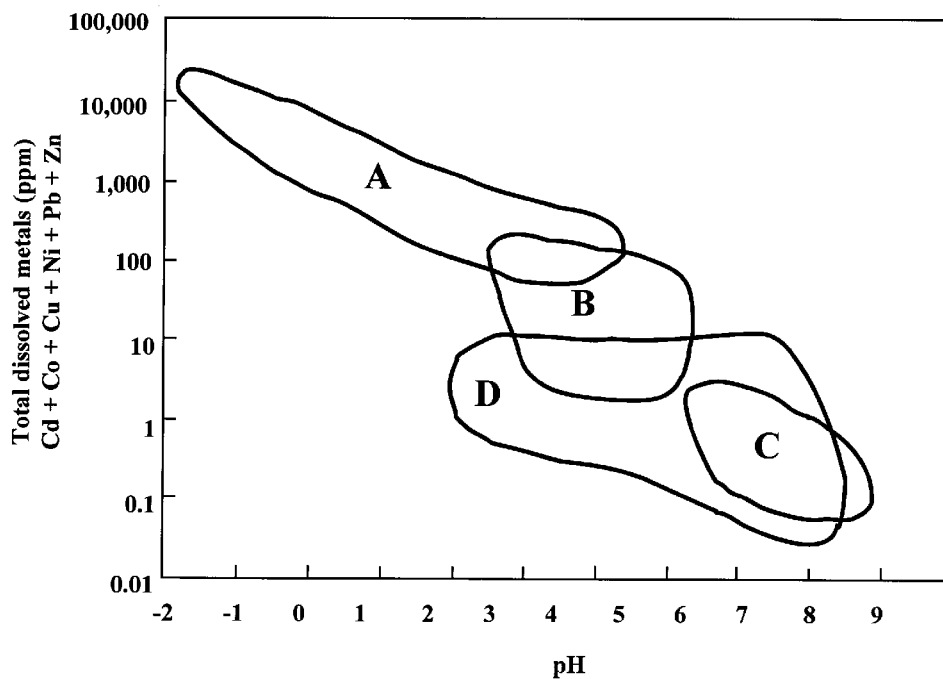


Figure 2. Ficklin plot (Plumlee and others, 1993) showing aqueous metal contents and pH ranges of water associated with volcanic massive sulfide deposits. Fields A, B, and C (Plumlee and others, 1994), are those for West Shasta, Calif., district VMS deposits, sulfide-mineral-rich vein deposits in rocks with low buffering capacity, and sulfide-mineral-rich vein deposits in carbonate host rocks, respectively. Field D is the composite field for water draining Prince William Sound, Alaska, VMS deposits (Goldfarb and others, in press).

Examples

Cyprus-type: Skouriotissa, Cyprus; Betts Cove, Newfoundland; Turner-Albright, Oreg.; Big Mike, Nev.
 Kuroko-type: Kidd Creek, Ontario; Iron King and Penn Mine, Calif.; Mokuroko district, Japan.
 Besshi-type: Besshi, Japan; Windy Craggy, British Columbia.

Spatially and (or) genetically related deposit types

VMS deposits are associated with a number of other mineral deposit types (Cox and Singer, 1986). Some VMS deposits, especially the Besshi-type deposits as broadly defined by Slack (1993), are transitional in depositional setting with some sedex deposits (Model 31a), such as Sullivan, British Columbia. VMS deposits are commonly associated with regionally developed iron- and (or) manganese-rich metalliferous sediment and chert developed at the same time-stratigraphic horizon as the massive sulfide deposits. Some Archean VMS deposits may be transitional to volcanic-associated iron formation. VMS deposits, especially in Archean terranes, tend to be spatially associated with shear-hosted mesothermal lode gold deposits (Model 36a) and Algoma-type banded iron formation (Model 28b).

Potential environmental considerations

Volcanic-associated massive sulfide deposits are among the most likely of all deposit types to have associated environmental problems, particularly acid mine drainage. Analyses of water draining VMS deposits plot in the extreme metal-extreme acidity field (fig. 2). VMS deposits have high iron- and base-metal-sulfide mineral contents and are hosted by rocks with low buffering capacity. These minerals are unstable under normal oxidizing near surface conditions and represent potential sources of highly acid and metal-rich drainage, especially in areas disturbed by surface mining or tailings disposal. Associated high abundances of potentially toxic trace metals, including arsenic, bismuth, cadmium, mercury, lead, and antimony, are present in some deposits, particularly those associated with felsic volcanic or sedimentary source rocks.

Exploration geophysics

Electrical properties of sulfide minerals, combined with large sulfide mineral concentrations in VMS deposits, make this type of mineral deposit a particularly favorable target for location by a variety of geophysical techniques. Self-potential, induced polarization, and a wide range of electromagnetic methods have been successfully used to locate buried VMS deposits. Pyrrhotite-rich and magnetite-bearing massive sulfide deposits may be locatable by detailed magnetic surveys. Airborne multispectral remote sensing techniques have been used to identify areas that contain hydrothermally altered rock and stressed vegetation that may be associated with mineralized rock.

References

Franklin and others (1981), Ohmoto and Skinner (1983), Fox (1984), Lydon (1984, 1988), Franklin (1993), and Slack (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Historically, most economic deposits are in the 1-5 million tonnes range (Singer, 1986c,d; Singer and Mosier, 1986). Deposits of this size can still be developed in areas with an existing mining infrastructure; however, development of new deposits in frontier areas likely requires at least 10 million tonnes of reasonably high grade ore. Most Cyprus-type deposits contain less than 15 million tonnes of ore. Most Besshi-type deposits are also fairly small; notable exceptions include the >300 million tonne Windy Craggy, British Columbia, deposit. Kuroko-type deposits, especially those of Precambrian age, can be very large, such as the world class Kidd Creek, Ontario, deposit.

Host rocks

Cyprus-type deposits are hosted by submarine mafic-volcanic rocks and their altered equivalents, typically in brecciated rocks commonly associated with pillow lavas, which have good buffering capacity. Host-rocks for Kuroko-type deposits range from basalt to rhyolite, which have high and low buffering capacities, respectively. Many deposits are associated with subaqueous dacitic-domes that have intermediate buffering capacity. Host rocks are commonly brecciated and are typically moderately to highly altered. Some deposits are hosted by associated volcanoclastic or hemipelagic sedimentary rocks that overly submarine volcanic sequences. Besshi-type deposits are typically hosted by turbiditic to hemipelagic graywacke interbedded with or intruded by basalt.

Surrounding geologic terrane

Submarine volcanic activity is a defining characteristic of VMS deposits. Most VMS deposits, including many ophiolite-hosted deposits of the Cyprus-type, are associated with arc-related volcanism. Local extensional tectonic environments are particularly conducive to deposition of massive sulfide deposits. Many VMS deposits are in rocks that have undergone collisional tectonism and may be in structural contact with a wide variety of rock types.

Wall-rock alteration

Footwall alteration is moderate to locally intense around most VMS deposits. Hanging-wall alteration is typically absent, but may be weakly developed in some deposits. Many deposits that have not been tectonically disrupted are underlain by "stringer-zone" mineralized and altered rock. Stringer-zones are characterized by anastomosing quartz-sulfide veins. Local zones of silicification are present near and within mineralized zones. The most common alteration is pervasive chloritization, which is less well developed with increasing depth and distance from hydrothermal upwelling zones, in the footwall of deposits. Deposits hosted by felsic rocks typically have extensively developed quartz sericite alteration in the footwall. Most altered rock associated with massive sulfide deposits has low to very low acid buffering capacity. Some massive sulfide deposits are associated with pervasive carbonate alteration in the footwall (for instance, Sturgeon Lake, Ontario; Morton and others, 1990). These carbonate alteration zones typically have low to moderate abundances of calcitic to ankeritic carbonate minerals. Massive sulfide deposits with associated carbonate alteration assemblages that are easily accessible to acid water are less likely to produce acid drainage.

Nature of ore

Massive sulfide deposits, by definition, contain zones or lenses of massive sulfide minerals, many with sulfide mineral contents exceeding 90 volume percent. Most deposits also contain extensive zones of semi-massive sulfide rock (25 to 50 volume percent) that contain economically exploitable ore. Stringer zone ore zones typically contain 5 to 20 volume percent sulfide minerals, hosted in quartz veins and disseminated in chloritic wall rocks.

Disseminated sulfide rock is extensively developed in footwall alteration zones; sulfide mineral abundances decrease with depth below the massive sulfide zone horizon. Lateral development of disseminated pyrite can be continuous for large distances at and immediately below the stratigraphic horizon of the massive sulfide lens.

Deposit trace element geochemistry

Iron is nearly always the predominant metal in sulfide phases. Economically exploitable VMS deposits associated with mafic rocks are variably enriched in copper and zinc, whereas those that contain a significant component of

felsic volcanic or sedimentary rock are relatively enriched in zinc and lead. Deposits associated with mafic rocks can contain anomalous concentrations of gold, silver, and cobalt. Deposits associated with felsic volcanic and sedimentary rocks contain minor to significant concentrations of lead, silver, arsenic, antimony, cadmium, and locally bismuth, tin, and selenium.

Ore and gangue mineralogy and zonation

The dominant sulfide mineral in most VMS deposits is pyrite, but pyrrhotite is dominant in others. Marcasite, which is present either intergrown with fine grained pyrite or as a replacement product of pyrrhotite, is generally a minor constituent but can constitute a potential source of acidic drainage because of its high reactivity relative to pyrite. The other dominant phases include sphalerite and chalcopyrite, accompanied by galena in VMS deposits associated with felsic rock. Other ore minerals are present in much lower abundances, but constitute important potential heavy metal sources. The most common accessory sulfide and sulfosalt minerals are those of the tennantite-tetrahedrite series, arsenopyrite, and various lead-antimony-bismuth sulfosalt minerals, particularly in deposits associated with felsic rock. Deposits associated with mafic rock may contain cobalt sulfide or thiospinel. Magnetite is present in some deposits and barite can be very abundant in Kuroko-type VMS deposits, in which it commonly forms an important ore facies. Gypsum and anhydrite are also abundant in some Kuroko deposits. The most common silicate gangue minerals are quartz and chlorite, which are accompanied by sericite in deposits associated with felsic rocks. Other gangue phases are much less abundant, except in massive sulfide deposits that have been metamorphosed to greenschist or higher metamorphic grades. In these metamorphosed deposits, phases such as anthophyllite and cordierite form from chloritic protoliths.

Metal zoning is well developed in massive sulfide deposits. Copper abundances are elevated in footwall and stringer ore zones, and zinc content increases upward and outward from the core of hydrothermal upwelling zones. In felsic-associated deposits, lead, arsenic, and antimony abundances are enriched upward and outward from the zinc-rich zones. Barite and silica are also enriched toward the stratigraphic tops and distal edges of most Kuroko-type deposits.

Mineral characteristics

Grain size is highly variable and is generally controlled by primary sulfide mineralogy and the extent of metamorphic recrystallization. Primary sulfide minerals of most zinc-lead-copper deposits are fine grained and intergrown, whereas those of most copper-zinc deposits are coarser grained (Franklin, 1993). The extent of grain size changes depends upon pressure and temperature conditions attained during metamorphism, and on the ductility of sulfide minerals. For example, cataclastic deformation significantly reduces grain-size and therefore reactivity of brittle sulfide minerals such as chalcopyrite and pyrite, but plastically deforms ductile sulfide minerals such as galena. Thermal metamorphism commonly causes sulfide ore to become much coarser grained and develop mosaic or porphyroblastic sulfide textures (Stanton, 1972).

Secondary mineralogy

Both initial seafloor and later near surface oxidation of massive sulfide minerals results in the formation of iron-rich gossan. Intermediate stages of oxidation also can result in the formation of a wide range of iron- and base-metal sulfate and sulfate-hydrate minerals. These highly soluble minerals are potentially important reservoirs of heavy metals that can be easily mobilized and potentially can produce high peak loads of dissolved metals if hydrologic conditions are suddenly altered, for example, by surface mining of a deposit in a wet climate. Secondary minerals formed in temperate climates include goethite, crystalline and amorphous silica, jarosite, a variety of metal-bearing hydroxy-sulfate minerals (beudantite, plumbojarosite, argentojarosite, woodhouseite, beaverite, meta-aluminite, hinsdalite, and brochantite), scorodite, native gold, native silver, native bismuth, barite, anglesite, litharge, covellite, chalcocite, digenite, enargite, luzonite, and acanthite.

Topography, physiography

These deposits have no specific topographic or physiographic features.

Hydrology

These deposits exert no specific influence on the adjacent hydrologic regime, partly because of their relatively small size. The extent of mineralized outcrop and (or) mine-related excavations exposed to the atmosphere or oxidized groundwater, and their position relative to the water table, are hydrologic factors that can significantly influence the

intensity and scale of environmental problems related to VMS deposits. Availability of oxidizing water is a controlling factor for acid generating potential and dissolved metal carrying capacity of water interacting with massive sulfide deposits or their mine-related products.

Mining and milling methods

Mining methods have a large influence on the potential environmental impacts of massive sulfide deposits. Both open-pit and underground methods have been used to mine VMS deposits in historic and modern operations. Local climatic and hydrologic conditions influence the acid generating capacity of deposits. Most massive sulfide deposits contain a large excess of iron-sulfide minerals relative to valuable base-metal sulfide minerals. The nature of ore processing and the method of deposition of the sulfide-mineral-rich tailings and waste rocks are critical parameters that influence the scope of environmental impacts associated with mining massive sulfide deposits. Fine-grained and intergrown sulfide minerals may require very fine grinding, which can result in highly reactive tailings, for beneficiation. Many modern mines discharge fine-grained sulfide-mineral-rich tailings into surface tailings ponds underlain by a number of impermeable linings. Previous mining operations often discharged tailings in a manner that resulted in significant contamination of surface and shallow ground water. Some active underground mines are able to dispose of essentially all tailings by backfilling and cementing mined stopes; consequently, surface contamination is virtually eliminated. Base-metal sulfide minerals are typically separated by flotation; some surfactants used in the process are toxic. Most of these surfactants are recycled and relatively minor amounts are discharged to tailings ponds.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Natural drainage water: Published data concerning the chemistry of natural drainage associated with VMS deposits include: Goldfarb and others (in press), Prince William Sound, Alaska; Greens Creek Environmental Impact Statement (1983), Admiralty Island, Alaska; and Filipek and others (1987), West Shasta, Calif., district. Temperate rainforest climate--Water draining Cyprus- and Besshi-type VMS deposits in the Prince William Sound area is dilute calcium-bicarbonate-type water (5.8 mg/l Ca and 15 mg/l HCO_3^-) that is slightly acidic to neutral (pH 6.4 to 7.6); the type of host rock, sedimentary or volcanic, does not seem to affect these generalizations. Specific conductance is <50 uS/cm. Metal abundances in this water include 20 $\mu\text{g/l}$ iron, 15 $\mu\text{g/l}$ aluminum, <2 $\mu\text{g/l}$ arsenic, 1.4 $\mu\text{g/l}$ zinc, and <1 $\mu\text{g/l}$ silver, copper, cobalt, chromium, lead, molybdenum, and antimony. Stream water flowing over undisturbed mineralized rock above several deposits has slightly elevated metal abundances, including as much as 40 $\mu\text{g/l}$ iron, 2 $\mu\text{g/l}$ copper, and 52 $\mu\text{g/l}$ zinc; pH varies from 5.6 to 7.3. Montaine, semi-arid climate--Natural water draining unmineralized areas above the West Shasta district (Filipek and others, 1987) also is calcium bicarbonate-type water (14 mg/l calcium and 22 mg/l HCO_3^-) that has a pH of 6.15 and a specific conductance of 100 uS/cm. This water contains 8 mg/l iron, 18 mg/l aluminum, <12 mg/l copper, <10 mg/l zinc, and <1 mg/l arsenic.

Mine drainage water: Published data sources concerning the chemistry of mine drainage associated with VMS deposits include: Goldfarb and others (in press), Beatson and eight other mines in Prince William Sound, Alaska; Kilburn and others (1994, 1995), Holden mine, Wash.; Alpers and others (1991), Penn mine, Calif.; and Alpers and others (1991, 1994), Iron Mountain mine, Calif. Temperate rainforest climate--The most acidic and metal-rich mine water, draining from the base of well consolidated tailings piles of Besshi-type deposits, from two locations in the Prince William Sound, Alaska, has a pH of 2.6 to 2.7 and contains as much as 21,000 $\mu\text{g/l}$ iron, 3,600 $\mu\text{g/l}$ copper, 220 $\mu\text{g/l}$ lead, 3,300 $\mu\text{g/l}$ zinc, 30 $\mu\text{g/l}$ cobalt, 10 $\mu\text{g/l}$ cadmium, and 311 mg/l sulfate. The tailings are devoid of vegetation and the drainages support a rich growth of bright green, copper-loving, bryophyte algal mats. Slightly acidic (pH 4.3 to 6.6) mine water was identified at six other deposits. Maximum metal values are 310 $\mu\text{g/l}$ iron, 1,400 $\mu\text{g/l}$ copper, and 3,100 $\mu\text{g/l}$ zinc. Kilburn and others (1994) sampled acidic mine drainage from within adits and below consolidated tailings piles at the Holden Mine, a copper-zinc VMS in amphibolitic mafic volcanic rocks. Water within the adits has a pH of about 5 and metal concentrations of 370-580 $\mu\text{g/l}$ iron, 570-580 $\mu\text{g/l}$ copper, and nearly 5,000 $\mu\text{g/l}$ zinc. Effluent from tailings piles has a pH of 2.8 to 2.9 and contains 23,000 to 50,000 $\mu\text{g/l}$ iron, 21 to 53 $\mu\text{g/l}$ copper, and 130 to 3,800 $\mu\text{g/l}$ zinc. Montaine, semi-arid climate--The Iron Mountain mine contains the most acidic and metal-rich mine water ever recorded. Alpers and Nordstrom (1991) have reported pH values ranging between 1.5 and <-1.0. The first ever occurrence of pH values less than one were obtained for dripping mine water that was actively precipitating melanterite and other efflorescent metal-sulfate salts. This water contains as much as 11 weight percent iron, 2.3 weight percent zinc, 0.5 weight percent copper, and 76 weight percent sulfate, with 340 mg/l arsenic, 211 mg/l cadmium, 12 mg/l lead, and 29 mg/l antimony.

Metal mobility from solid mine wastes

Soluble sulfate salt minerals derived from weathering and oxidation of sulfide minerals in mine dumps and tailings piles represent a potential source of metal contamination and acid generation. As percolating surface and ground water evaporates during dry periods, efflorescent metal-sulfate salt minerals form encrustations around and below the base of the piles, which effectively stores acidity and metals released during sulfide mineral breakdown. Subsequent rainfall or snowmelt following a dry period is likely to release a highly concentrated pulse of acid mine water. Mine dumps associated with lead-rich VMS deposits (Kuroko-type) may be a source of lead contamination due to high concentrations of soluble secondary lead minerals.

Secondary minerals in tailings impoundments include a variety of iron oxyhydroxides (goethite, lepidocrocite, akaganeite, maghemite, and ferrihydrite), sulfates (gypsum, bassanite, jarosite, hydronium jarosite, melanterite, goslarite, ferrohexahydrite, epsomite, hexahydrite, siderotil, rozenite, anglesite, alunogen, and copiapite), and minerals such as marcasite, covellite, and native sulfur (Jambor, 1994). Pore water from tailings impoundments associated with the Heath Steele, New Brunswick, deposit are acidic (pH 1.8 to 5.2), have Eh of 280 to 580 mV, and contain significant dissolved metal abundances, including 0.3 to 600 mg/l copper, 0.8 to 11 mg/l lead, 23 to 4,880 mg/l zinc, 1,200 to 36,000 mg/l iron, and 600 to 67,600 mg/l sulfate (Boorman and Watson, 1976). Similarly, pore water from tailings impoundments associated with the Waite Amulet, Quebec, deposit are acidic (pH 2.5 to 6.0), have Eh of 200 to 700 mV, and contain significant dissolved metal abundances, including as much as 65 mg/l copper, as much as 5 mg/l lead, as much as 250 mg/l zinc, as much as 8,000 mg/l iron, and as much as 20,000 mg/l sulfate (Blowes and Jambor, 1990). Finally, pore water from tailings impoundments associated with the Kidd Creek, Ontario, deposit are acidic (pH 3.5 to 7.5), have Eh of 50-500 mV, and contain significant dissolved metal abundances, including 0 to 38 mg/l copper, 0 to 2 mg/l lead, 0 to 6,200 mg/l zinc, 0 to 350 μ g/l arsenic, 1 to 990 mg/l iron, and 1,860 to 27,000 mg/l sulfate (Al and others, 1994).

Extremely fine grinding required for beneficiation of VMS ore may enhance airborne transport of lead-arsenic-cadmium-antimony-bearing dust. This phenomenon is most probable in semi-arid to arid regions in which strong winds prevail.

Soil, sediment signatures prior to mining

The elemental suite and magnitude of geochemical anomalies in soil and sediment collected from undisturbed VMS deposits depend upon a number of factors, including VMS deposit type, extent of ore outcrop or overburden, climate, topography, etc. Stream sediment samples collected below Kuroko-type deposits in temperate rain forest on Admiralty Island, Alaska, contain 5 to 10 weight percent iron, as much as 10,000 ppm barium, hundreds to several thousand ppm zinc, hundreds of ppm lead, tens to hundreds of ppm arsenic, copper, and nickel, as well as 0 to 20 ppm silver, bismuth, cadmium, mercury, molybdenum, and antimony (Kelley, 1990; Rowan and others, 1990; Taylor and others, 1992; C.D. Taylor, unpub. data, 1995).

Stream sediment geochemical signatures associated with undisturbed to variably disturbed Cyprus and Besshi VMS deposits in the Prince William Sound, Alaska, are similar to those just described. They contain 10 to 40 weight percent iron, several hundred ppm barium, hundreds of ppm arsenic and zinc, tens to hundreds of ppm lead, hundreds to thousands of ppm copper, and 0 to 20 ppm silver, bismuth, mercury, molybdenum, and antimony (R.J. Goldfarb, unpub. data, 1995).

Potential environmental concerns associated with mineral processing

Tailings ponds below mills are likely to contain high abundances of lead, zinc, cadmium, bismuth, antimony, and cyanide and other reactants used in flotation and recovery circuits. Highly pyritic-pyrrhotitic orebodies that are exposed to oxidation by air circulating through open adits, manways, and exploration drill holes may evolve SO₂ gas; in some cases, spontaneous combustion can cause sulfide ore to burn. Tailings that contain high percentages of non-ore iron sulfide minerals have extremely high acid-generating capacity. Surficial stockpiles of high-sulfide mineral ore are also potential sources of metal-rich mine water.

Smelter signatures

Most base-metal rich ore concentrates are smelted. In most cases, concentrates are shipped to custom smelters, and therefore do not contribute to the environmental impact in the immediate mine vicinity. Larger districts are often served by a smelter co-located in the district. Data compiled by Gulson and others (1994) document the relationship between lead in soil near smelters and blood lead in children; similar data for the Leadville, Colo., area indicate similar trends. Additional data may be available for the Trail, British Columbia and El Paso, Tex. smelters.

Climate effects on environmental signatures

Great differences between geochemical mine drainage data for deposits in the West Shasta, Calif., district, eastern Canada, and that for deposits in cooler and wetter Alaskan climates underscore the important role of climate with regard to acid mine drainage associated with VMS deposits. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. In wet climates, high water tables may reduce exposure of abandoned orebodies to oxidation and continually flush existing tailings and mine dumps. Although metal-laden acid mine water does form, it may be diluted to benign metal abundances within several hundred meters of mixing with a higher order stream.

Geoenvironmental geophysics

Self potential detects electrical potentials produced by ongoing redox reactions. The method is suitable for locating "hot spots" in tailings piles. Electromagnetic surveys are useful for tracing and monitoring metal-bearing ground water. In addition, detailed magnetic data can help delineate geologic contacts, strata, and fractures that may act as fluid conduits, especially in crystalline rocks.

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